Journal of Hazardous Materials 172 (2009) 826–832

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Partitioning characteristics and particle size distributions of heavy metals in the O_2/RFG waste incineration system

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ARTICLE INFO

Article history:
Received 23 October 2008
Received in revised form 19 June 2009
Accepted 18 July 2009
Available online 25 July 2009

Keywords:
Incineration
O_2/RFG combustion
Heavy metals
Particle size distribution

ABSTRACT

This study applies the oxygen/recycled flue gas (O_2/RFG) combustion technology for waste incineration and investigates the effects of different RFG rates on the concentrations of gas pollutants as well as the partitioning characteristics and particle size distributions of five heavy metals (Cr, Cu, Pb, Zn, and Cd). Experimental results show that the combustion efficiency can be improved and the concentration of CO_2 is increased by appropriately controlling the RFG rate in the O_2/RFG incineration system. The partitioning characteristics and size distributions of heavy metals in O_2/RFG combustion system are different from those in general air combustion system. Under O_2/RFG combustion system, the partitioning percentages of heavy metals in sand bed, bottom ash, and collected ash are increased. The particle size distributions of heavy metals display the triple-peak curves. As the RFG rate rises, the concentrations of volatile heavy metals are increased in small-size (<1 μm) fly ash, decreased in medium-size (1–10 μm) fly ash and increased in large-size (>10 μm) fly ash. These phenomena will benefit to increase the overall control efficiency of heavy metals in the incineration system.

1. Introduction

As global warming and climate change due to greenhouse effects and air pollution are continuing serious, how to effectively improve the combustion efficiency and mitigate the emissions of greenhouse gas CO_2 and other pollutants becomes an international and imperative issue. Most of the CO_2 in the atmosphere are emitted from the anthropic activities; especially those involving the combustion processes. CO_2 is an inert gas and is hard to dissolve in water as well as react with chemical absorbents. In addition, the concentrations of CO_2 in the exhaust gas of general air combustion processes are usually lower than 15% due to the supplied air only containing 21% O_2. Therefore, the CO_2 gas emitted from general air combustion system is hard to be separated and captured by the air pollution control technologies, such as physical adsorption/absorption, chemical absorption, cryogenic distillation, and membrane separation [1–4]. On the other hand, the major gas of supplied air (79% N_2) in general air combustion processes is released as exhaust gas and thus consumes a lot of heat energy. As a result, the oxygen/recycled flue gas (O_2/RFG) or O_2/CO_2 combustion technology has been developed and applied in the coal-fired power plants in Japan and Europe. Its basic principle is to separate nitrogen out of the air, then the pure oxygen is mixed with the recycled flue gas (the major gas is CO_2) to serve as the feed gas. The amount of exhaust gas can be significantly reduced, the heat efficiency can be improved, and the CO_2 concentration in the exhaust gas can be much enhanced (even higher than 90%). All of these advantages are beneficial for the separation, control and recovery of CO_2 and other air pollutants [5–12]. Most references related to the O_2/RFG combustion technology focused on the CO_2 emission control in the coal-fired power plants [6,8,13,14]; however, fewer researches applied this technology in other combustion processes such as waste incineration.

The emission of heavy metals from waste incineration presents potential environmental and health hazards. Heavy metal compounds cannot be destroyed at high temperatures, but can be volatilized or reacted with other elements to form metallic vapors or sub-micro particles during waste incineration. Therefore, the formation and partitioning characteristics of heavy metals in waste incineration system are highly emphasized and extensively studied. From the comprehensive review of related references, the formation, behaviors and partitioning of heavy metals in a combustion system as well as the leaching property of heavy metals in bottom ash and fly ash are majorly affected by the operation conditions (such as combustion temperature and gas flow rate), the chemical property and reactivity of heavy metals (such as volatility and reaction affinity) and the waste compositions (such as the content of chlorine and sulfur) [15–17]. Wey et al. [18] indicated that the partitioning percentages of heavy metals in the sand bed of a fluidized bed incinerator followed the sequence of chromium > lead > cadmium, and this sequence was just the reverse order of volatility. Chen et al. [19] found that the increase of

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0304-3894/$ – see front matter
doi:10.1016/j.jhazmat.2009.07.074

combustion temperature would enhance the vaporization rate of heavy metals. The decreased temperature in the follow-up cooling system and air pollution control devices (APCDs) (such as the semidry scrubber) could reduce the formation of gaseous heavy metals and increase the content of heavy metals in fly ash. Lima et al. [20] addressed the fact that fuel is the main factor influencing Cd and Cr form, concentration and extractability from the MSW fly ashes. Flue gas temperature was also very important in the dictation of heavy metal integration on fly ash fraction. Verhulst and Buekens [21] indicated that the increased content of sulfur in feedstock promoted the formation of stable metal sulfides and such promotion effects were suppressed as the combustion temperature higher than 800 °C. Zhang et al. [22] studied the effect of sulfur compounds (including sulfur, sulfide, sulfite and sulfate), initial concentration of heavy metal and operating conditions on Cd emission in municipal solid waste (MSW) incineration using a simulated tubular furnace and simulated MSW spiked with Cd. The results showed that S and Na_2S tended to increase Cd partitioning in bottom ash, whereas Na_2SO_3 and Na_2SO_4 tended to reduce Cd partitioning in bottom ash. The effect of sulfur compounds on Cd partitioning in bottom ash was in the sequence of $Na_2S > S > Na_2SO_3 > Na_2SO_4$. Lighty et al. [23] showed that the presence of chlorine in feedstock can increase the formation of metal chlorides as well as the volatility of heavy metal compounds and sub-micro particulates during incineration processes. Belevi and Langmeier [17] addressed the fact that the partitioning characteristics of heavy metals were majorly influenced by the combustion temperature but the effects of excess air factor (or oxygen content) were not evident.

The concentration distributions of heavy metals in the fly ash of waste incineration are also influenced by the particle size of fly ash. Wey et al. [24] showed a trend on the distributions of heavy metals Pb, Cr, and Cd in fine fly ash. More volatile heavy metals (Pb and Cd) had higher concentrations in the fly ash of small particle size (0.1–15.72 μm); and most of less volatile heavy metal (Cr) were present in the fly ash of large particle size (37–125 μm). Both the organic chlorides and inorganic chlorides in the feedstock could increase the formation of metal chlorides and decrease the range of particle size distribution. Itkonen and Jantunen [25] used a five-stage cascade impactor to analyze the particle size distribution of fly ash at the outlet of cyclone in a coal-fired power plant. They found that the mass size distribution of fly ash behaved as a single-peak distribution. Mulhalland and Sarofim [26] used a small tube furnace to study the particle size distributions of heavy metal nitrates (Pb, Cd, and Ni) with the aerodynamic diameter of 0.4–15 μm. Their experimental results showed that the particle size distributions of three metals displayed a three-peak distribution curve. Kauppinenl and Pakkanen [27] indicated the particle size distributions of fly ash and heavy metals were both bimodal. The concentrations of heavy metals Pb, Ca, V, Cu, Sr, and Cd in fine fly ash were very high. The particle size distribution of Cd tended to accumulate in small particles. Norton et al. [28] showed the concentrations of heavy metals As, Cd, Cu, Ni, Pb, and Zn in the fly ash of a coal-fire power plant and a RDF incinerator were enhanced with fine particles. Yuan et al. [29] indicated that heavy metals Pb, Cd, Zn, Cu and Cr were present mainly in the solid phase with a solid to gas ratio (S/G) of over 12.3. However, Hg appeared mainly in the gas phase with an S/G ratio from 0.15 to 1.04 because it has a low boiling point. The partition of heavy metals in the solid and gas phases was dominated by the boiling point of metals. The particle size distribution of PM was bimodal, with the most present in the fine mode. Finer particles contained more Pb, Cd, Zn and Cu, whereas coarser particles contained more Cr and Hg. Zhang et al. [30] showed that most of the Hg and Cd were evaporated and then removed by air pollution control (APC) system through condensation and adsorption processes, thus being enriched in the fine APC residues particles. Cr, Cu, and Ni were transferred into the APC residues mainly by entrainment, and distributed uniformly in the two residues flows, as well as in the ash particles with different sizes. Pb and Zn in the APC residues were from both entrainment and evaporation, resulting in the higher concentrations (two to four times) compared with the bottom ash. Arsenic was transported into the flue gas mainly by evaporation, however, its transfer coefficient was lower.

Since O_2/RFG combustion technology is still in development stage and most previous researches focused on the CO_2 emission control in a power plant, the application of this technology in waste incineration is never studied. In addition, the emission characteristics of heavy metals in general air combustion processes are well studied; however, the effects of flue gas recycling on the partitioning characteristics of heavy metals are less investigated. Therefore, this study applies the O_2/RFG combustion technology for waste incineration and investigates the behaviors of different heavy metals in different parts of waste incineration system as well as the size distributions of heavy metals in fine fly ash. The results will provide useful information for the future development of O_2/RFG combustion technology and the control of heavy metals during waste incineration.

2. Experimental

2.1. Apparatus and materials

The schematic diagram of experimental apparatus is shown in Fig. 1. The composition and concentration of feed gas for incineration are mixed by a pure oxygen cylinder, an air compressor, a recycled pump, flow meters and a gas mixer. For a better control of combustion temperature, a fluidized bed incinerator is used as the experimental reactor. The fluidized bed incinerator was equipped with a rotary feeder, a gas distributor, a main combustion chamber, and a heating system. The combustion chamber had 50 cm height and 5 cm inside diameter, and was made of 3 mm thick stainless steel (AISI 310). Five thermocouples are inserted into the axis of combustion chambers at equal interval (12 cm) and the flue pipes to determine the temperature profiles. Silica sands are used as the fluidized bed materials and their particle size distribution was 15.05% 470–300 μm, 49.62% 300–214 μm, 17.35% 214–163 μm, and 12% <163 μm. Because the silica sands in the fluidized bed incinerator have higher heat capacities and better mixing efficiency, the temperature distribution in the combustion chamber is uniform and stable.

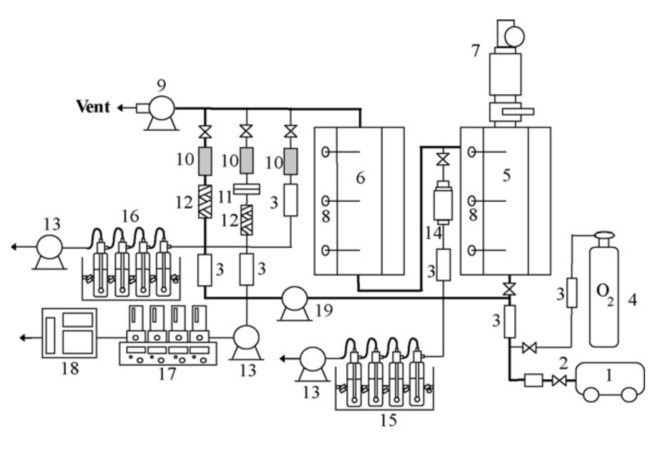

Fig. 1. Schematic diagram of experimental apparatus. (1) Air compressor, (2) dehumidifer, (3) float meter, (4) oxygen cylinder, (5) first combustion chamber, (6) second combustion chamber, (7) rotary feeder, (8) thermocouple, (9) induced fan, (10) fly ash collector, (11) filter, (12) water vapor condenser, (13) sampling pump, (14) cascade impactor, (15) heavy metal impingers, (16) HCl impinger, (17) dilution system, (18) NDIR gas analyzer, and (19) recirculation pump.

For precisely controlling the content of heavy metals in the feedstock, the mixtures of granular coal and polyvinyl chloride (PVC) pellets (with 2–3 mm particle size) are used as the feed materials and to simulate the normal municipal solid waste. In Taiwan, the major components in the MSW are paper, kitchen garbage and plastics. For stable and continuous feeding in the experiments, granular coal is used to represent the paper and kitchen garbage and PVC pellets to represent the plastic waste. The weight ratio of coal and PVC in the feedstock is 4:1, and this value is within the reasonable range for the ratio of paper + kitchen garbage and plastics in the MSW. Five heavy metals (lead, cadmium, cadmium, copper and zinc) are added into the granular coal by impregnation method. The concentrations of heavy metals in coal are chromium 100 mg/kg, cadmium 50 mg/kg, zinc 1500 mg/kg, copper 1500 mg/kg, and lead 1000 mg/kg. Those values are determined with reference to the contents of heavy metals in the MSW of Taiwan [31]. The feed materials are continuously fed into the combustion chamber by a rotary feeder on the top of the incinerator.

2.2. Procedures

Before starting the experiment, the first and secondary combustion chambers are preheated by electric heaters to 800 °C and 1000 °C, respectively. The composite feed gas is introduced into the incinerator to verify the system is airtight and their concentrations are correct. After the temperatures in combustion chambers reach the steady state, the experiment starts and the simulated waste are continuously fed into the incinerator at a feeding rate of 7 g min^{-1}. During the experiments, a temperature monitoring system and a flue gas analyzer are employed to continuously monitor the temperature variations in each unit and the concentrations of CO_2, SO_2, NOx, CO and O_2 in the flue gas to ensure that the combustion behaviors are stable. The recycled flue gas is treated with a filter to remove the fly ash and a condenser to remove water vapor, and then delivered into the fires combustion chamber by a recycled pump. All the experiments are controlled at the same excess oxygen factor. The O_2 concentration and the total flow rate of feed gas are controlled at 21% and 50 l min^{-1}, respectively. Herein the total flow rate of feed gas equals to the flow rate of composite gas plus the flow rate of recycled flue gas. Table 1 lists the detailed operation conditions in each experiment. The total flow rates of feed gas for the experiments performed at the same O_2 concentrations are controlled identically even though the ratios of recycled flue gas are different.

2.3. Sampling and analysis

For precisely understanding the partition characteristics of heavy metals in each unit of incineration system, the experimental apparatus can be disassembled to take the samples completely. A H_2O_2/HNO_3 impinger is also employed to collect the heavy metals in gas phase. After the experiment is finished and the temperatures are cooled down, all the quartz sand, bottom ashes, fly ashes and wall ashes in the combustion chamber and flue pipes are taken out. The bottom ash and quartz sand are separated by two standard sieves (70 mesh and 100 mesh). The sieving is performed using a sieve-shaking machine at the frequency of 200 rpm for 10 min. These samples are weighed and digested by the aqua regia and a microwave digester. The concentrations of heavy metals in the digested solutions are analyzed by an Inductively Coupled Plasma-Atomic Emission Spectroscope (ICP-AES) (PerkinElmer Optima 2100DV).

In order to understand the partition characteristics of heavy metals in different sized particles, an Anderson cascade impactor (Tokyo Dylec, Model AS-500) is installed at the exit of first combustion chamber to collect the particles with different diameters. The Anderson cascade impactor has eight collecting plates, in which the range to collect particles include >29.25 μm, 19.2–29.25 μm, 12.6–19.2 μm, 8.7–12.6 μm, 5.4–8.7 μm, 2.82–5.4 μm, 1.73–2.82 μm, 1.2–1.73 μm and 0.45–1.2 μm by a filter. The sampling flow rate is 7 l/min, the sampling time takes 3 min, and the maximum sampling temperature can reach to 800 °C. According to the sampling temperature, the cutoff diameter of collected particles must be calibrated. After the sampling by Anderson cascade impactor is finished and the temperature is cooled down, the eight collecting plates and filter in the impactor are disassembled in sequence. Each plate is separately placed in a desiccator and then weighted in a precise scale room where the temperature and humidity are well controlled. After that, the eight collecting plates are put in a beaker and 20 ml pure water is added to vibrate for 200 min by a supersonic vibrator. Particles on the collecting plates will be vibrated to water solution. Finally, the solutions are digested by microwave digester and analyzed for the concentration of heavy metals by the ICP-AES. During the analysis of heavy metals, the standard additive method is implemented to control the analysis quality and the recovery is controlled in the range of 100 ± 15%.

3. Results and discussions

3.1. Gas concentrations at different RFG rates

Fig. 2(a)–(d) shows the concentrations of CO_2, CO, SO_2 and NO in the exhausts of O_2/RFG incineration system at different recycled flue gas (RFG) rates. In Fig. 2(a), the concentration of CO_2 in the flue gas is only 12% when no flue gas is recycled. Such combustion condition is same as that in the general air combustion system where CO_2 concentration is usually in the range of 10–15%. As the RFG rate increases, the concentration of CO_2 in the flue gas displays an

Table 1
Experimental conditions.

Run	Composite gas (l min^{-1})			RFG (4) (l min^{-1})	*R* (5) (%)	TFEG (6) (l min^{-1})	CO_2 (7) (%)	*m* (8)
	O_2 (1)	Air (2)	FCG (3)					
1	0	50	50	0.0	0	50	21	1.04
2	1.9	40.7	42.6	7.4	15	50	21	1.04
3	4.4	28.4	32.8	17.2	35	50	21	1.04
4	6.9	16.0	22.9	27.1	55	50	21	1.04
5	9.4	3.7	13.1	36.9	75	50	21	1.04
6	10.0	0.6	10.6	39.4	80	50	21	1.04

(3) FCG is the flow rate of composite feed gas (3) = (1) + (2).
(4) RFG is the flow rate of recycled flue gas.
(5) *R* is the percentage of recycled flue gas, which is defined as (amount of recycled flue gas)/(amount of total flue gas).
(6) TFEG is the total flow rate of feed gas into the incinerator (6) = (3) + (4).
(7) CO_2 is the concentration of oxygen in total feed gas.
(8) *m* is the excess oxygen factor, which is defined as (amount of oxygen in feed gas)/(stoichiometric amount of oxygen).

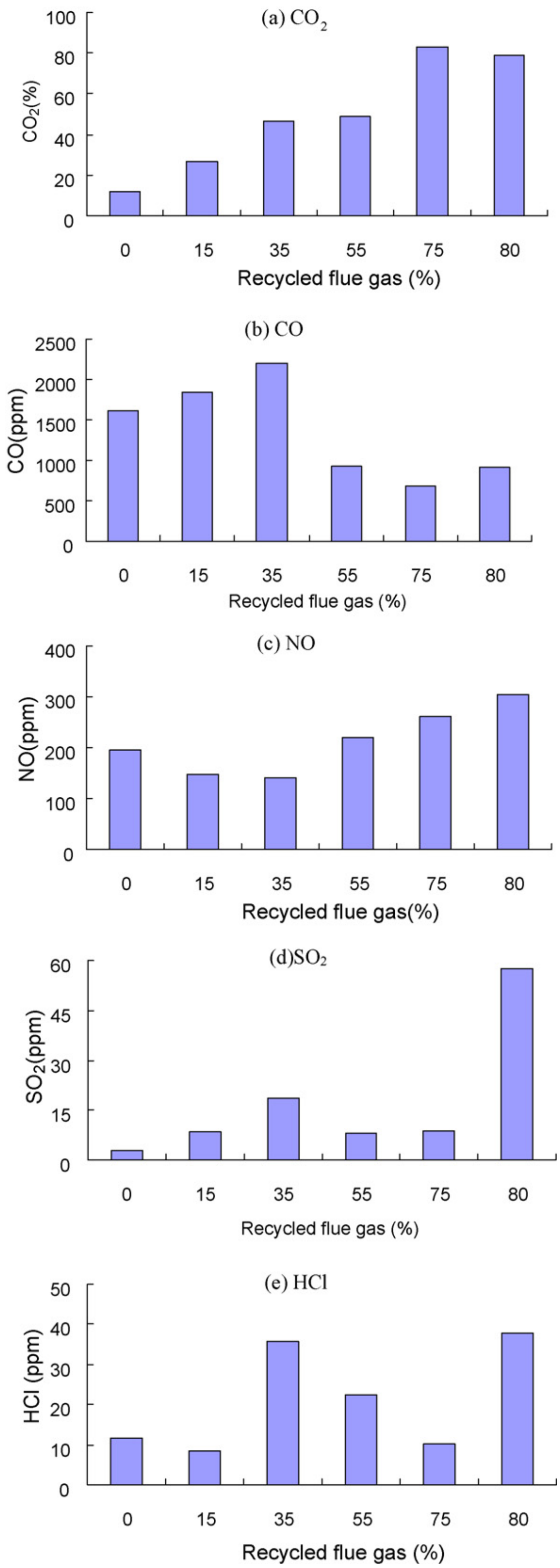

Fig. 2. Concentrations of gas pollutants in the exhausts of O_2/RFG incineration system at different recycled flue gas rates: (a) CO_2 (b) CO (c) NO (d) SO_2 (e) HCl.

increasing trend. The maximum concentration of CO_2 can reach up to 83% when the RFG rate is 75%. Such enhancement effect on the CO_2 concentration is attributed to the significant reduction on the amount of exhausts as the RFG rate increases [32]. This property of O_2/RFG combustion technology is beneficial to CO_2 separation and recovery by commercial adsorption devices. However, the CO_2 concentration slightly drops to 78% as the RFG rate increases to 80%. Because the great quantity of recycled flue gas cannot be well pressurized and delivered; the pressure of feed gas is reduced at such high RFG rate. The quality of fluidization in the sand bed as well as the mixing of solid waste and recycled gas becomes worse. The concentration of CO_2 is therefore dropped.

Fig. 2(b) shows the concentration of CO in the flue gas at different RFG rates. The concentrations of CO in the flue gas are enhanced with raising the RFG rates from 0% to 35% and then dramatically decreasing at 55–80% RFG rates. Because CO is a major produce of incomplete combustion, it is an important indicator to evaluate the combustion efficiency. The lower concentration of CO means the better combustion efficiency. The results demonstrate that the overall combustion efficiency of O_2/RFG incineration system can be better than that of traditional air incineration system at high RFG rates. Because the average retention time of combusted gas in O_2/RFG system is prolonged, the destruction efficiency of organic components and CO can be more complete [33,34]. Fig. 2(c) shows the concentration of NO at different RFG rates. With rising RFG rates, the concentration of NO decreases and then increases gradually. It is well known that recycling flue gas is an alternative method to diminish the formation of NO; however, the enhancement effect on the concentration of exhaust gas will overcome the de-NOx effect at relative high RFG rate. The concentration of NO is therefore increased.

Fig. 2(d) and (e) shows the concentrations of SO_2 and HCl at different RFG rates respectively. It can be seen that the concentrations of SO_2 and HCl also increase with the RFG rates but some irregular results are observed. Similar results are obtained in the double-check experiments. Because SO_2 and HCl are easily dissolved in the water vapors produced from waste incineration, these acid vapors in the flue gas are massively removed by two de-moisture devices before recycling flue gas and gas analysis. So the concentrations of SO_2 and HCl are relatively low and the irregular results are obtained.

3.2. *Partitioning characteristics of heavy metals at different RFG rates*

Fig. 3(a)–(e) shows the partitioning percentages of cadmium, chromium, copper, lead and zinc in each part of incineration system at different RFG rates, where silica sand is the fluidized medium and bottom ash is the residue after the combustion of feedstock, the fluepipe ash is the fly ash partitioned on the walls of flue pipes, the collector ash is the fly ash captured by the simple ash collector, the filter ash is the smallest fly ash collected by a glass-fiber and located behind the ash collector, and the gas phase represents the gaseous vapors of heavy metals which were captured by the impinger liquids. The mass of heavy metals in each part of incineration system are summed up and compared with the mass of heavy metals in feedstock to check the mass balance of heavy metals. Experimental results illustrate that the mass balances of heavy metals in each experiment lie within $100 \pm 20\%$, which demonstrates that the experimental procedures and results in this study are accurate and reliable.

Fig. 3(a) shows the partitioning characteristics of chromium in the incineration system at different RFG rates. Because chromium is less volatile, most of them are present in silica sand, bottom ash and fluepipe ash when no flue gas is recycled. The same results can be found in previous studies [17,18,21]. When the RFG rates increase, the partitioning percentages of chromium in silica sand and bottom ash are slightly increased. The partitioning percentages in collector ash, filter ash, and gas phase are very few. Almost 100% of chromium can be completely controlled and captured in the incineration system.

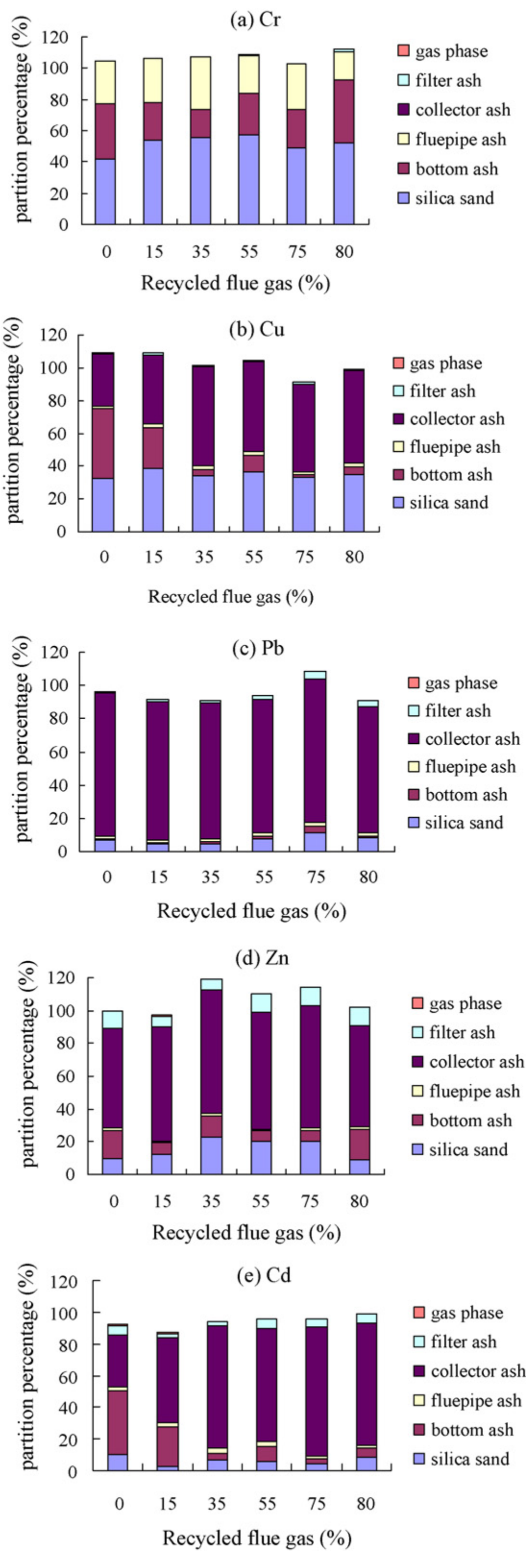

Fig. 3. Partitioning percentages of heavy metals in each part of incineration system at different recycled flue gas rates: (a) Cr, (b) Cu, (c) Pb, (d) Zn, and (e) Cd.

Fig. 3(b) shows the partitioning characteristics of copper in the incineration system at different RFG rates. Because copper is more volatile than chromium, less copper is present in silica sand and more copper is present in collector ash. When the RFG rates increase, the partitioning characteristic of copper is significantly different from that of chromium; the percentage of copper in silica sand slightly increases, whereas bottom ash decreases, and the percentage in collector ash obviously increases, even more than that in silica sand and bottom ash. Although the partitioning characteristics of copper are different from those of chromium, almost 90–100% of copper can be effectively controlled and captured in the incineration system. The effects of RFG rates on the partitioning characteristics of copper are more obvious than those of chromium.

Fig. 3(c) shows the partitioning characteristics of lead in the incineration system at different RFG rates. Because lead is a highly volatile heavy metal, most of it is partitioned in collector ash and less is in sand bed and bottom ash. With an increase of RFG rate, the partitioning percentage of lead in sand bed (silica sand and bottom ash) slightly increases. This result indicates that the recycling of flue gas is beneficial to lead captured in sand bed. The maximum percentage of lead captured in sand bed occurs at 75% RFG rate. In addition, the percentage of lead in filter ash is increased with the RFG rates and thus the emission of lead in gas phase is reduced. The results demonstrate that O_2/RFG combustion technology has great effects in controlling volatile lead.

Fig. 3(d) shows the partitioning characteristics of zinc, whose volatility is between lead and cadmium. Therefore, zinc also mainly distributes in collector ash, whereas the percentage of zinc in bottom ash, silica sand and filter ash is higher than that of lead. When the RFG rates rise, the percentage of zinc in silica sand increases, roughly reduces in bottom ash and increases in filter ash. On the whole, applying O_2/RFG combustion technology can increase the percentage of zinc in collector ash, silica sand and filter ash, and reduce the emission of zinc in gas phase.

Fig. 3(e) shows partitioning characteristics of cadmium in the incineration system. Cadmium has the highest volatility among these five heavy metals [15]; therefore less cadmium is captured in sand bed and mostly partitioned in collector ash and filter ash instead. With the rising RFG rates, the percentage of cadmium captured in silica sand slightly increases; however, the percentage of cadmium in bottom ash is obviously reduced and greatly increased in collector ash. Because flue gas recycling increases the concentration of cadmium in the incineration system, the condensation and coagulation effects on the gas-phase cadmium and sub-micro particles are enhanced to form larger particles. The results also demonstrate that O_2/RFG combustion technology indeed benefits the capture and control of heavy metals in the flue gas. Most of volatile heavy metals can be captured in the air pollution control devices of O_2/RFG combustion system and thus reduce their emissions in gas phase.

In summary, the partitioning percentage of heavy metals in each unit of incineration system depends on their volatility at 0% RFG rate (same as general air incineration system). Less volatile heavy metals, such as chromium and copper, are mostly partitioned in sand bed (silica sand and bottom ash). Highly volatile heavy metals, such as zinc, lead and cadmium, are mostly partitioned in collector ash and filter ash. O_2/RFG combustion technology makes less change on the total portioning percentages of less volatile metals chromium and copper, whereas increasing the percentages of volatile metals lead, zinc and cadmium in collector ash and silica sand/bottom ash. The percentages of volatile heavy metals in gas phase are reduced, which is beneficial in increasing the overall control efficiency of heavy metals in a waste incineration system.

3.3. Particle size distribution of heavy metals at different RFG rates

Fig. 4(a)–(e) shows the particle size distributions of chromium, copper, lead, zinc and cadmium in the fine fly ash of O_2/RFG incineration system. The fly ashes of different particle size are separated and collected by an Anderson cascade impactor. In Fig. 4(a), the concentration of chromium increases with the particle size of fly

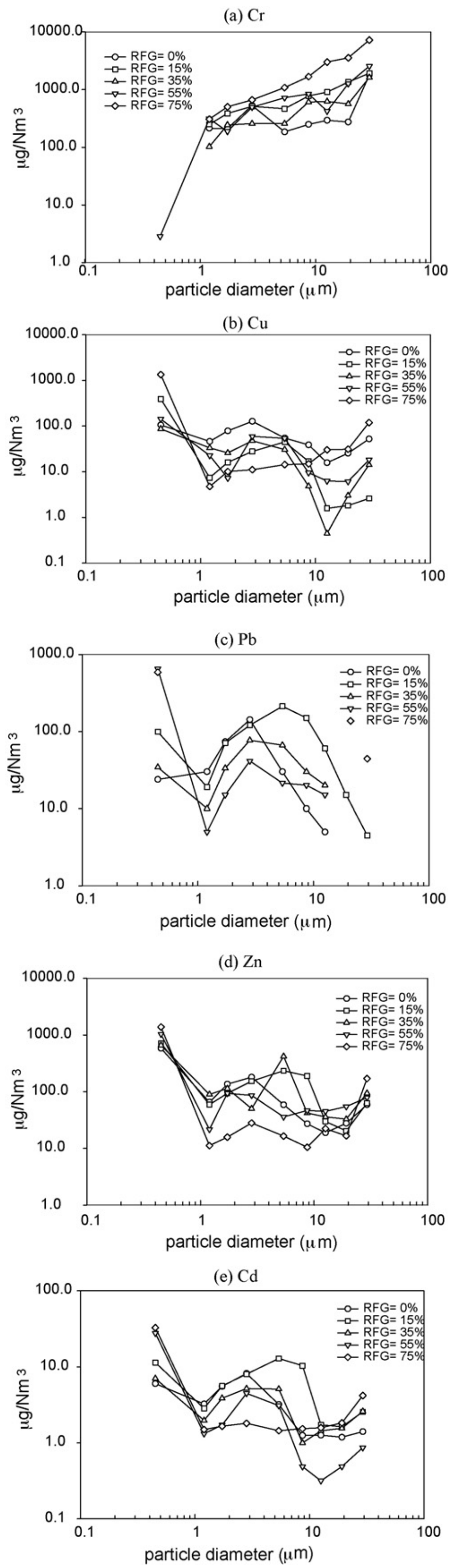

Fig. 4. Particle size distributions of heavy metals in the fine fly ash of O_2/RFG incineration system: (a) Cr, (b) Cu, (c) Pb, (d) Zn, and (e) Cd.

ash. Because chromium is less volatile, it will not be volatilized to form gaseous vapors and condensed or coagulated on the fine particles. As the RFG rates rise, the concentrations of chromium in each size range of fly ash mostly increases. This result shows that O_2/RFG combustion technology can increase the formation of chromium on larger particles and improve the control efficiency of heavy metals.

Fig. 4(b) shows the particle size distribution of copper is different from chromium, displays triple peaks at 0.45 μm, 2.82 μm and 29.25 μm respectively. The concentration of copper in fine particle (0.45 μm) is higher than those in larger particle sizes (2.82 μm and 29.25 μm). With the rising RFG rates, the concentrations of copper in each size range of fly ash are mostly decreased except in 0.45 μm particles.

Fig. 4(c) shows that the particle size distribution of volatile lead displays single peak (2.82 μm) at 0% RFG rate. With flue gas recycling, the particle size distribution shows double peaks, which appear in the size of 0.45 μm and 2.82 μm (RFG = 35% and 55%), 0.45 μm and 5.4 μm (RFG = 15%) as well as 0.45 μm and 12.6 μm (RFG = 75%) respectively. The rise of RFG rate can increase the concentration of lead in small-size fly ash, decreasing in medium-size fly ash and increasing in large-size fly ash. Because flue gas recycling increases the concentration of lead in the incineration system, the condensation and coagulation effects on the gas-phase lead and medium-size particles are enhanced to form small-size and large-size particles respectively. The increased concentrations of lead in small and large particles are beneficial to improve the control efficiency of volatile lead in the incineration system.

Fig. 4(d) shows that the particle size distribution of zinc displays triple peaks at 0% RFG rate, which appear as 0.45 μm, 2.82 μm and 29.25 μm respectively. When flue gases are recycled, the size distributions also show triple peaks, in which the size changes to 0.45 μm, 5.4 μm and 29.25 μm (RFG = 15% and 35%), 0.45 μm, 1.73 μm and 29.25 μm (RFG = 55%) as well as 0.45 μm, 2.82 μm and 29.25 μm (RFG = 75%) respectively. With an increase in RFG rate, the partitioning characteristics of zinc are similar to those of lead, increasing in small-size and large-size fly ash and decreasing in medium-size fly ash. The increased concentrations of zinc in small and large particles are beneficial to improve the control efficiency of zinc in the incineration system.

Fig. 4(e) shows the particle size distribution of highly volatile cadmium. Without flue gas recycling, the particle size distribution shows double peaks, which appear at the smaller size (0.45 μm and 2.82 μm). When flue gas recycled, the size distribution shows triple peaks, for which the size changes to 0.45 μm, 5.4 μm and 29.25 μm (RFG = 15%), 0.45 μm, 2.82 μm and 29.25 μm (RFG = 35% and 55%) as well as 0.45 μm and 29.25 μm (RFG = 75%) respectively. With an increase in RFG rate, the size distribution of cadmium increases in small-size fly ash, decreases in medium-size fly ash and increases in large-size fly ash. This phenomenon is similar to that of lead and zinc.

4. Conclusions

From the results of this study, it can be found that the combustion efficiency can be improved and the concentration of CO_2 can be enhanced by appropriately controlling the RFG rate in the O_2/RFG incineration system. The partitioning characteristics and size distributions of heavy metals in O_2/RFG combustion system are different from those in general air combustion system. Under O_2/RFG combustion system, the partitioning percentages of heavy metals in sand bed, bottom ash, and collected ash are increased. The particle size distributions of heavy metals mostly display the triple-peak curves. As the RFG rate rises, the concentrations of volatile heavy metals are increased in small-size (<1 μm) fly ash, decreased in medium-size (1–10 μm) fly ash and increased in large-size (>10 μm) fly ash. These phenomena will benefit to increase the overall control efficiency of heavy metals in the incineration system.

Acknowledgements

The authors gratefully acknowledge the National Science Council of R.O.C. (Taiwan) for the financial support under project no. NSC 94-2211-E-241-001.

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